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FEASIBILITY STUDY AND DEMONSTRATION OF VARIABLE-THRUST PROPULSION FOR A SOFT-LANDING VEHICLE

by

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ABSTRACT. The soft-landing vehicle was designed and tested to demonstrate the feasibility of using the NOTS Variable Area Injector to softly land a rocket vehicle without the aid of aerodynamic forces. The vehicle was tested in a "vertical track" which restricted freedom of movement to the direction of the vertical axis.

Propellant tank capacity of the soft-landing vehicle was 200 pounds of inhibited red fuming nitric acid and 100 pounds of unsymmetrical-dimethylhydrazine. Total loaded weight of the vehicle was 700 pounds and maximum thrust was 1,300 pounds.

The vehicle successfully completed four captive flight tests. During these tests a maximum height of 155 feet and landing velocities between 3.8 and 8.3 feet per second were achieved. Thrust control was sufficient to allow the observer to hover the vehicle.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

January 1963

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

One of the engineering problems involved in placing a man on the moon is the soft-landing of the manned lunar module. In early 1959, the U. S. Naval Ordnance Test Station (NOTS) postulated that a NOTS variable-thrust propulsion system could be used as the retro-propulsion system. NOTS designed, built, and flight tested in early 1961 a vehicle, conclusively demonstrating that a variable-thrust propulsion system could be precisely controlled to softly land a vertically descending craft.

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This report was reviewed for technical accuracy by E. Yim, E. G. Swann, and R. L. McAlexander.

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FIG. 1. L064839; FIG. 2. L065787; FIG. 3. L073645; FIG. 4. L068101; FIG. 5. L072902; FIG. 6. L059301; FIG. 7. L060917; FIG. 8. L063779; FIG. 9. L067431; FIG. 10. L067429; FIG. 11. L072692; FIG. 12. L075670; FIG. 13. L075672; FIG. 14. L075671.

INTRODUCTION

After the initial success of the NOTS Variable Area Injector, this station was naturally interested in determining if this particular variable-thrust device had uses other than the one for which it had been developed. Perhaps the most apparent use of a variable thrust is that of controlling the descent of a vehicle without the aid of aerodynamic forces. It was therefore decided to determine if the NOTS Variable Area Injector offered sufficient control of thrust to allow its use in soft vertical landing applications. A second use for the soft-landing vehicle was as a test vehicle for an optical scanner guidance system which was to be designed and built at NOTS.

The complexity and expense of an attitude-control system made consideration of a free-flight vehicle impractical. It was found to be feasible to modify existing facilities to provide a vertical track which would allow a soft-landing vehicle freedom of movement only in a vertical direction.

Design of the vehicle was begun in February 1960 and fabrication was completed in June of that year. However, from this point progress was slow, since higher priority projects absorbed available manpower until late 1960. The first captive flight of the soft-landing vehicle was made on 28 April 1962 and was a complete success.

TEST VEHICLE

The soft-landing vehicle was designed for ruggedness and low cost of construction in order to prove feasibility with a limited amount of funds. Surplus hardware was used wherever possible, partially accounting for the somewhat unorthodox appearance of the vehicle (Fig. 1). The vehicle was far from optimum as far as weight of inert hardware was concerned.

PROPULSION

The heart of the variable-thrust propulsion system was the NOTS Variable Area Injector. A sectional view of this injector and combustion chamber appears in Fig. 2.

The variable-thrust development program was initiated at the Naval Ordnance Test Station in 1955. The initial purpose of the program was to provide a propulsion system to meet the operational requirements of a long range, air-to-air missile which required thrust

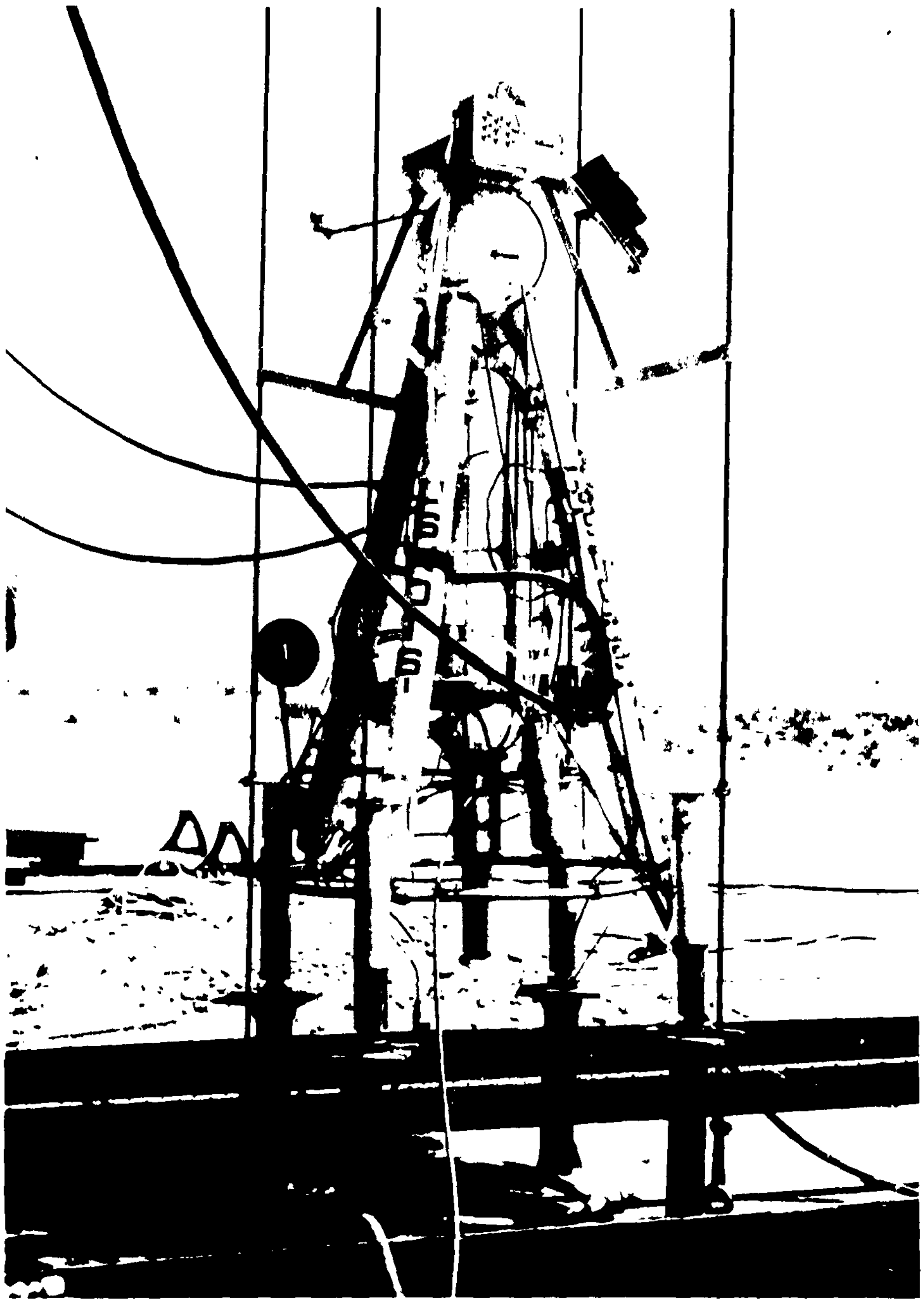

FIG. 1. Vehicle Installed in Vertical Track.

FIG. 2. Sectional View of Chamber and Injector.

control. Feasibility of the variable area injector principle was established in August 1958. The injector, which was used in the soft-landing vehicle, was designed and developed by NOTS for use in an Army supported surface-to-surface missile feasibility demonstration.

Thrust is controlled by a single moving part in the injector, the pintle. Positional change of this part varies the annular area of both the fuel and oxidizer orifices, thus regulating the amount of propellant allowed to flow into the combustion chamber. The position of the pintle is controlled by a hydraulic fluid. This injector has demonstrated full range thrust control up to 16 cycles per second (cps). Test on an advanced experimental injector indicates that frequencies up to 30 cps can be obtained with proportional thrust control, which is satisfactory for most applications. The thrust controlling element, the pintle, can be positioned with an accuracy of one percent of its full travel movement. Measured characteristic exhaust velocity (C^*) efficiency as high as 96 percent was obtained with this engine using unsymmetrical-dimethylhydrazine (UDMH)and inhibited red fuming nitric acid (IRFNA) as propellants. A schematic diagram of the servo system appears in Fig. 3.

The early development of the NOTS Variable Area Injector has been covered in detail.[1] The development of the injector and combustion chamber used in the soft-landing vehicle has been covered in a report on the development of the liquid propellant variable-thrust sustainer motor for the Automet Missile "A".[2]

The soft-landing vehicle used an Astrolite plastic-lined combustion chamber in the first two tests. This chamber had a maximum thrust of 950 pounds at 450 psi chamber pressure, but could not provide sufficient thrust to allow the optical scanner to land the vehicle. To obtain sufficient thrust for the guidance system control, it was necessary to develop a combustion chamber capable of at least 1,250 pounds thrust. A graphite-lined combustion chamber, which produced 1,300 pounds thrust at 300 pounds per square inch (psi) chamber pressure, was developed. It is interesting to note that the lowest touch-down velocity was achieved with the 1,300-pound thrust combustion chamber.

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[1] U. S. Naval Ordnance Test Station. Design and Preliminary Evaluation of a Variable Thrust Rocket Motor, by D. Marshall Klein. China Lake, Calif., NOTS IDP 567. CONFIDENTIAL.

[2] ------. The Development of the Liquid Propellant Variable Thrust Sustainer Motor for the Automet Missile "A", by D. H. Strietzel and others. China Lake, Calif., NOTS, November 1961. (NAVWEPS Report 7789 NOTS TP 2782), CONFIDENTIAL.

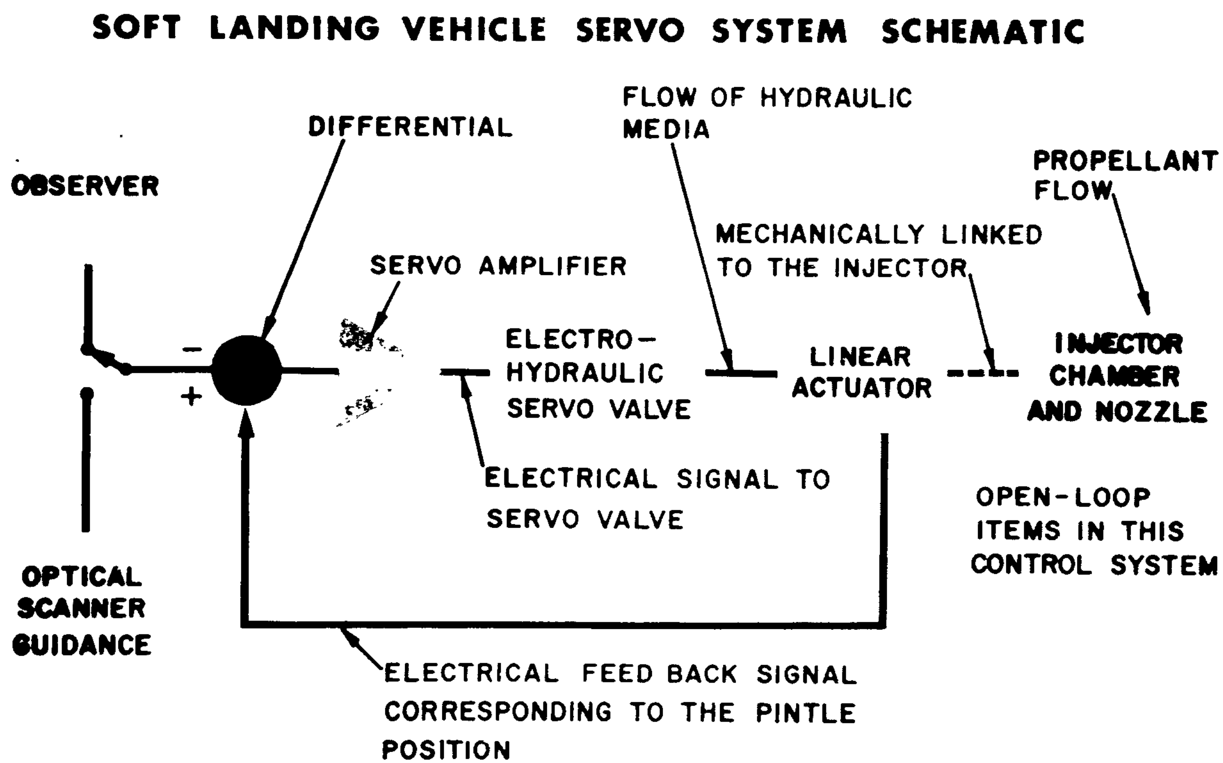

FIG. 3. Schematic Diagram of Servo System.

The pressurized tank method of propellant pumping was employed, and nitrogen gas at 3,000 psi was stored in a spherical tank mounted on top of the vehicle. A pressure regulator reduced the nitrogen pressure to 600 psi for propellant tank pressurization.

The engine used unsymmetrical-dimethylhydrazine as fuel and inhibited red fuming nitric acid as the oxidizer, giving the vehicle a capacity of 300 pounds of these hypergolic (propellants ignite when mixed) propellants. A detailed description of the structure, tankage, and plumbing appears in Appendix A.

GUIDANCE

Providing a test vehicle for the optical scanner guidance system was a secondary purpose of the soft-landing vehicle. The optical scanner produces a frequency which is proportional to the rate of change of the line of sight to some object in the field of view. When mounted on the soft-landing vehicle, the frequency of the output signal is proportional to the ratio of velocity of the vehicle to the height of the vehicle.

According to theory, if the retro-thrust were controlled in such a manner as to cause the frequency of this signal to remain constant, both the velocity and height of the vehicle would approach zero simultaneously. A photograph of the guidance package mounted on the vehicle can be seen in Fig. 4. Figure 5 is a picture taken during flight by a camera located on the vehicle with the same field of view as the optical scanner. Even with the low contrast shown in this photograph, the scanner produced good signals. A schematic diagram of the optical scanner appears in Fig. 6.

A detailed description of the optical scanner guidance system, as well as its performance, is available.[3]

TESTING

TEST FACILITIES

The soft-landing vehicle captive flight tests were held at the Randsburg Wash Test Range on a rocket launcher tower modified to

[3] U. S. Naval Ordnance Test Station. Optical Control System for Soft Landing, Final Report Feasibility Study, by C. E. Hendrix. China Lake, Calif., NOTS, (in process). (NAVWEPS Report 7890, NOTS TP 2883).

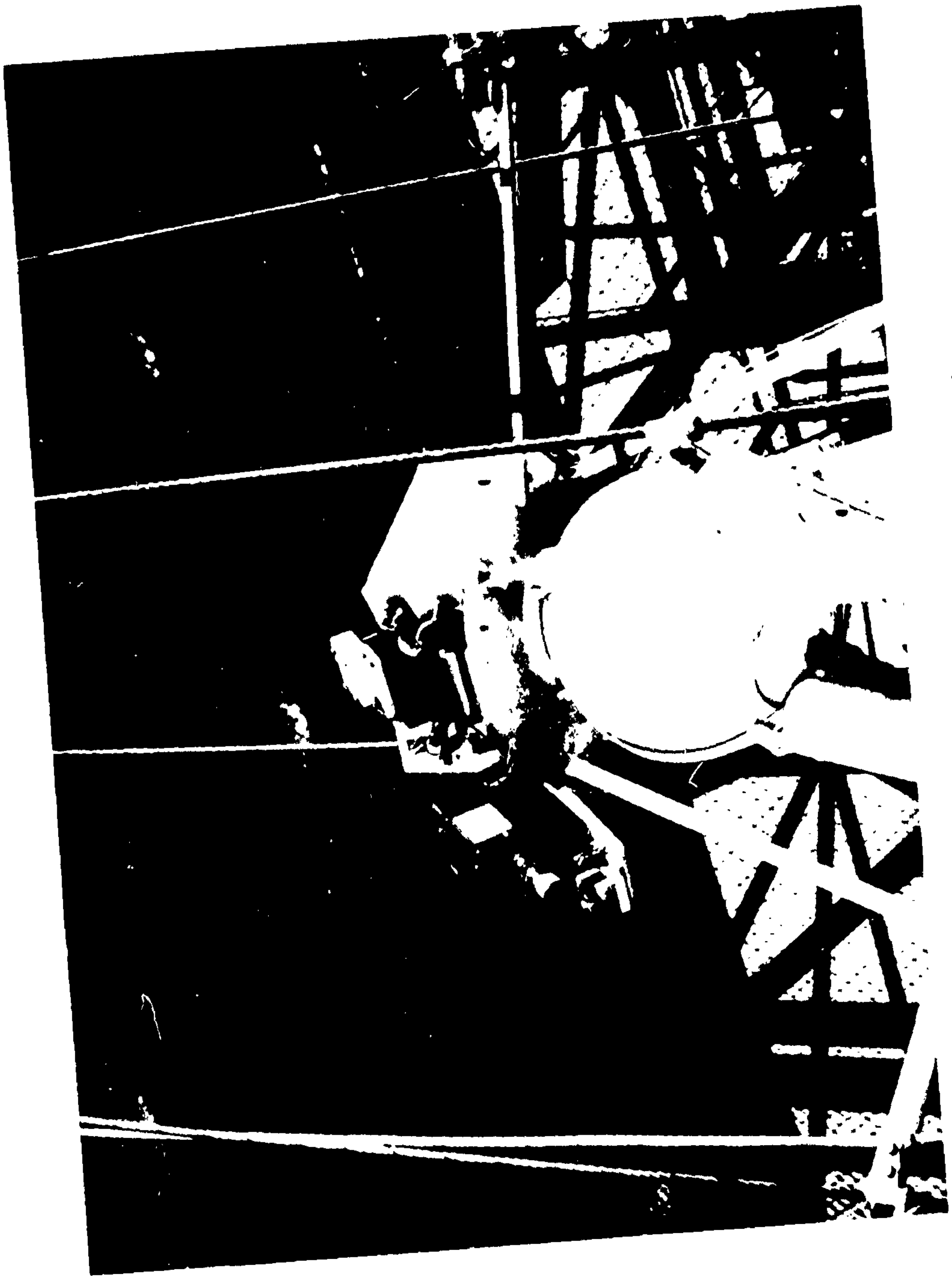

FIG. 4. Guidance Mounted on Vehicle.

FIG. 5. Background Viewed by Scanner.

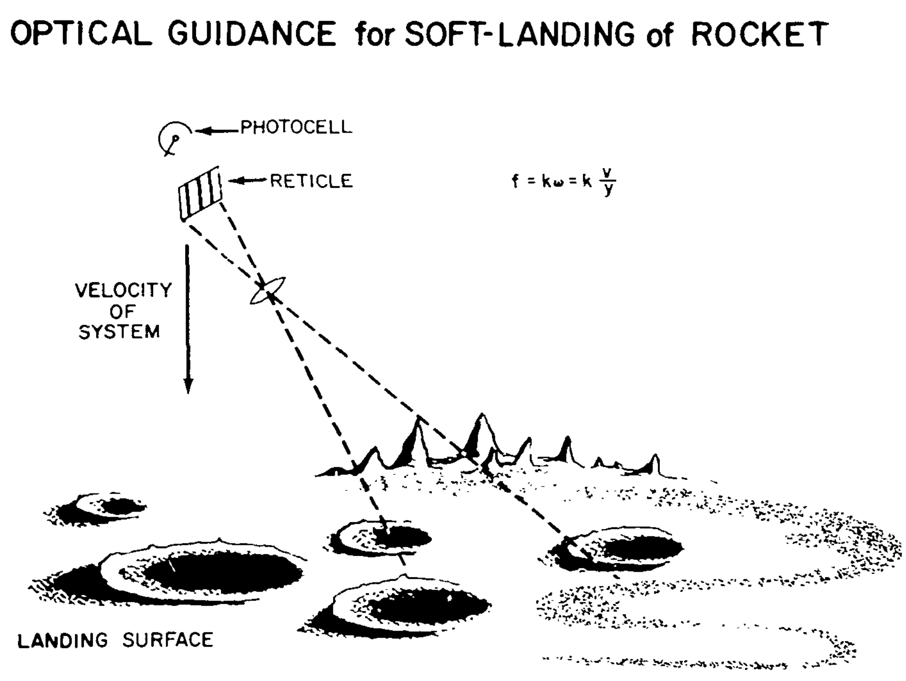

FIG. 6. Schematic of Guidance System.

provide a vertical track (Fig. 7). A piece of armor plate four inches thick, 12 feet wide by 16 feet long, was used as a landing pad. A blast deflector was built into the plate to deflect the hot exhaust gas away from the vehicle and to provide drainage in case of propellant spillage. The plate also provided a base for the attachment of the four 1/2-inch diameter steel cables which formed the vertical track. An overhanging platform at the top of the tower held the other end of the cables.

As water mains did not serve the test site, two fire trucks and two large tank trucks were required to provide water for the blast deflector and deluge system.

The data recording and test control equipment was located in an armored van approximately 200 feet from the base of the vertical track. An electrical cable link was used for control and instrumentation between the tower and van. The link between the vehicle and the tower was formed by three umbilical cables, which carried the propulsion instrumentation signals, the valve actuation signals, and the thrust command signal.

Guidance instrumentation signals were telemetered to another instrumentation van some distance from the test site.

The observer, who controlled the thrust of the vehicle, was stationed in a small armor-plated hut beside the test control van, with the vehicle visible through a small bullet-proof glass window in the front of the hut.

PREFLIGHT TEST

There were no static-test firings of the complete soft-landing vehicle system. The combustion chamber, injector, and servo system had been exhaustively tested both statically and in flight during the Missile "A" feasibility program. After installation in the vertical track, the vehicle was test fired, using inert propellant (hydraulic fluid as fuel and water as oxidizer). All instrumentation and control equipment, which was to be used in the captive flight test, was used in this test. The above test was also a check on the adequacy of the propellant loading and vehicle decontamination procedures.

All valves and instrumentation were checked out, and the variable area injector was operated using a hydraulic power supply prior to loading the propellant.

"ASTRONAUT" SELECTION TEST

Except for two brief periods during the fourth test, the vehicle's

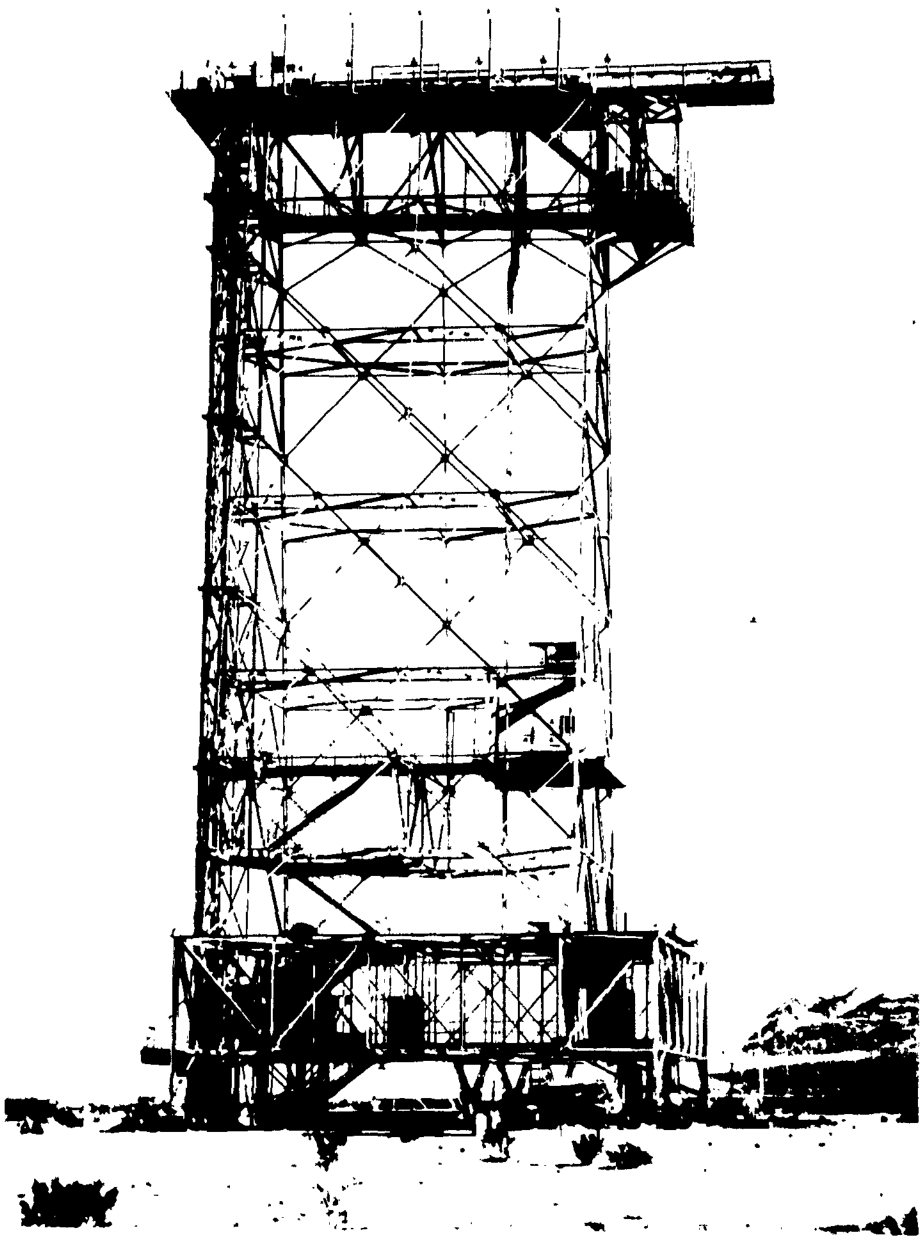

FIG. 7. 150-Foot Tower and Vertical Track.

variable-thrust engine was controlled by an observer. The vehicle velocity and position were controlled by an "astronaut," who determined by visual observation the thrust levels required. Perhaps the greatest unknown in the first test was the ability of the observer to send the correct thrust command signal to the vehicle.

To determine the feasibility of an observer correctly controlling the thrust of the vehicle, to select a person to control the vehicle in flight, and to give the prospective "astronaut" some practice, a program was set up on the analog computer to simulate the response of the soft-landing vehicle to thrust control. The throttle, which was to be used in the actual test, was used by the prospective "astronaut" to feed thrust-control signals into the computer.

Two lines, 150 (scale) feet apart, were drawn on the analog computer plotting table. One of these lines represented the ground; the other represented the overhanging portion of the tower which formed a stop at the end of the vertical track. The plotting pen, representing the vehicle, moved between the two lines at the theoretical scale velocity of the vehicle. The computer simulated the force of gravity and the thrust of the engine on the "vehicle", causing the plotting pen to accelerate according to the sum of these two forces. The prospective "astronaut", observing the position and velocity of the plotting pen, tried to make it rise to a scale height of 75 feet, hover, descend, and land softly by controlling the "thrust".

This analog computer program indicated that an observer could control the vehicle. However, it also illustrated the fact that even a small "pilot error" could be fatal. The probability of "pilot error" seemed to increase as the velocity of the vehicle increased. It became more difficult to estimate the amount of travel required for the vehicle to stop as the velocity of the "vehicle" increased.

The "astronaut" selection program played an important part in planning the "trajectory" of the first captive flight.

CAPTIVE FLIGHT TEST

The first of four captive flight tests of the soft-landing vehicle took place on 28 April 1961. The purpose of this test was to demonstrate the feasibility of achieving manually-controlled lift-off, hovering, and landing of the vehicle.

The vehicle ascended to approximately 75 feet, descended to 35 feet, hovered, and landed with touch-down velocity estimated at 8 feet per second. The observer, who controlled the thrust of the engine during the captive flight, stated that the vehicle was easier to control than was the plotting pen on the analog computer. Performance of the

vehicle during the test was exactly as expected. Figure 8 is a sequence photograph of the vehicle during the first test.

The second captive flight of the vehicle occurred on 5 June 1961. The purpose of this test was to determine the compatibility with the variable-thrust engine of the guidance package which was installed on the vehicle. Output of the optical scanner, signals from various sections of the guidance system circuit, and the vibration of the guidance mounting platform were monitored by telemetry. Instrumentation was added to sense vehicle height, and thrust of the engine was manually controlled throughout this test.

The time from lift-off to touch-down was approximately 50 seconds. The vehicle ascended to 130 feet, hovered, descended to 70 feet, hovered, descended to 15 feet, hovered, and landed. Velocity of the vehicle at touch-down was 8.3 feet per second. Sluggish response of thrust to thrust command signal was experienced in the latter part of the flight.

Instrumentation indicated that the nitrogen tank pressure had dropped to approximately 300 psi at the end of the test, which would cause the propellant tank pressures to drop to less than half the design pressure. The fuel was used as hydraulic fluid to actuate the pintle, so low fuel tank pressure would cause the pintle to lag behind the thrust command signal. Reduced propellant pressure would also require that the pintle move a greater distance to cause a given change in thrust than would be required if the propellants were at design pressure. Of course, the low propellant pressures would cause reduction in performance and in the maximum thrust obtainable from the engine. After the test, it was found that the oxidizer vent valve had developed a slight leak; and it is believed that leakage through this valve caused excessive use of nitrogen.

The data from the test indicated that the engine had little or no effect upon the operation of the optical scanner guidance system. A maximum value of 2 g's rms in the 0 to 1200 cps was determined for the vibration level in the guidance mounting platform. Some scanner noise attributable to vibration appeared shortly after lift-off when engine vibration was at a maximum. Neither dust nor exhaust gas affected the scanner output; however, the wind was in a favorable direction.

During a large portion of the descent in this test, the velocity of the vehicle was held too low to allow the guidance to produce a good signal. Minor changes in the guidance electronic circuits were found to be desirable, and the new information indicated that higher maximum thrust from the engine would be advantageous when the guidance system controlled the descent of the vehicle. It was therefore decided to develop a new combustion chamber which would produce 1,300 pounds

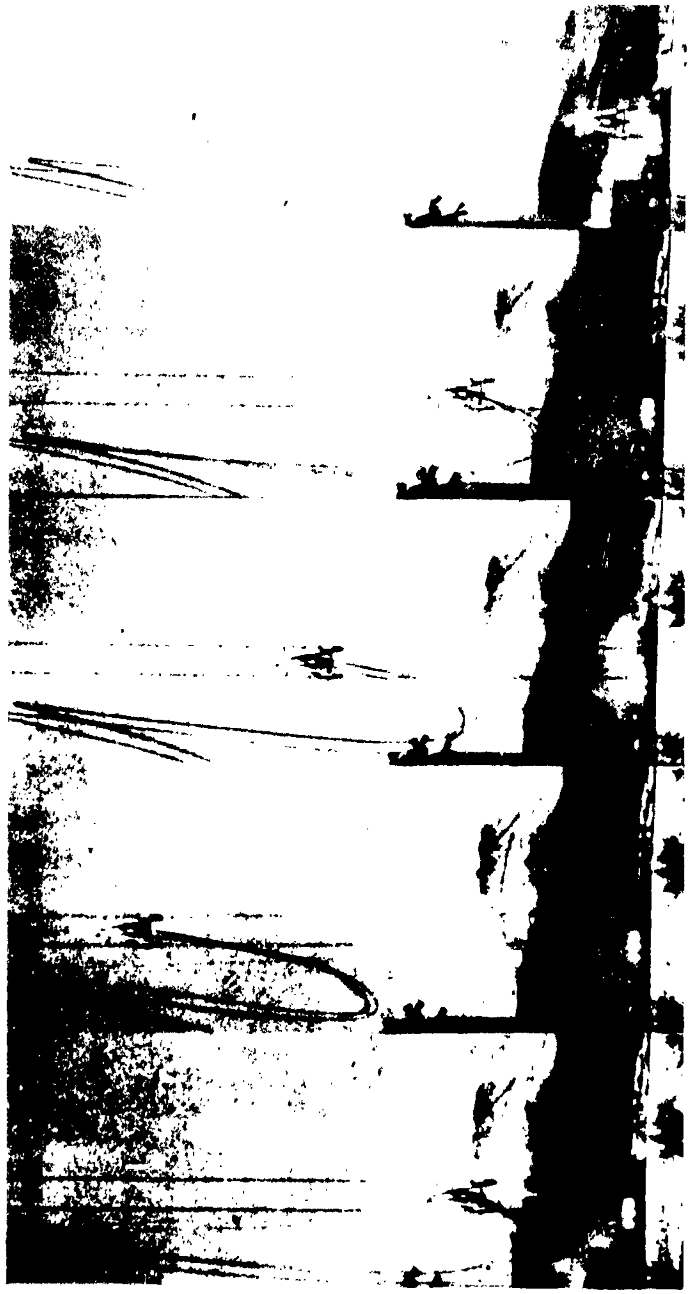

FIG. 8. Sequence Photograph - First Test.

thrust at 300 psi chamber pressure. The changes in combustion chamber and guidance system introduced unknowns into the next test. Also, it was desirable to monitor the signal of the guidance package under free-fall conditions, as a period of free fall was expected when the control of the engine was shifted from manual to the guidance system. For these reasons, it was decided to conduct another test with the engine under manual control.

The next three attempts to test the vehicle resulted in misfires. Two of the misfires were caused by failure of a weld between the injector and the propellant line, and it is believed that these welds were weakened when the injectors were installed in the vehicle and failed when the lines were pressurized. Both injectors had previously been static tested, and one had been used in an earlier captive flight test of the vehicle. These misfires resulted in flooding of the landing pad with propellant; however, little damage to the vehicle or guidance resulted. The other misfire was caused by a loose connection in the umbilical cable connector. This loose connection in the servo feedback circuit occurred after the final checkout of the servo system and was probably caused by the wind whipping the cables about.

The third captive flight of the vehicle took place on 14 September. The vehicle functioned properly, reaching a height of approximately 130 feet, and was dropped in free fall for 1.7 seconds, simulating the change from manual to guidance control of thrust. The touch-down velocity was 8 feet per second. Flight time was 36 seconds. Data indicated that the guidance package was functioning properly, and it was decided to allow the guidance to land the vehicle on the following day.

The object of the test on 15 September was to determine the feasibility of controlling the thrust with the optical scanner guidance package. Under manual control the vehicle rose to a height of 155 feet, a few feet from the top of the tower. At this point, the thrust of the engine was reduced to zero; and the control of the variable-thrust engine was shifted from the observer to the guidance package. The vehicle descended for several seconds, stopped, and began to accelerate toward the top of the tower. Since the nature of the scanner is such that it cannot distinguish direction of motion once the vehicle started upward, the scanner continued to call for more and more thrust in an attempt to hold the ratio of velocity-to-height constant. The observer took control of the engine and reduced the thrust to stop its ascent. Thrust of the engine was again reduced to zero, and the vehicle was allowed to enter free fall. Control of the engine was then switched to the guidance package, and the results were identical. The scanner called for thrust, which stopped the vehicle approximately 50 feet from the ground and reversed its motion. The pilot then took control of the vehicle and landed it. Touch-down velocity was 3.8 feet per second, and the vehicle was off the ground for 40 seconds. Figures 9 and 10

FIG. 9. 1105R Vehicle Just After Take-Off.

FIG. 10. 1105R Vehicle on Descent.

are photographs of the vehicle near the top of the tower just after take-off. Figure 11 shows the vehicle height plotted versus time.

The greatest vibration level observed during the last test series was approximately 4 g's rms over a 2,000 cps bandwidth which corresponds to a spectral density of $8 \times 10^{-3}\, g^2$ cps. There was little difference in the vibration level produced by the engine with the 950-pound thrust or with the 1,300-pound thrust combustion chamber.

An explanation of the malfunction of the guidance system during the final test would require a long discussion of the guidance system parameters which is beyond the scope of this report. The performance of the optical scanner guidance system during the soft-landing vehicle test is available in the final report feasibility study.[4]

During the decontamination of the vehicle after the 15 September test, a malfunction of the servo system resulted in an unscheduled flight which destroyed the vehicle. Throughout the captive flight test, the first step in decontamination of the vehicle was to operate the engine at a thrust level lower than the weight of the vehicle until the residual propellant in the vehicle tanks had been consumed. At the end of this last test, it became necessary to close the propellant valves until a large cloud of nitrogen tetroxide (N_2O_4) was dissipated. This cloud was caused by large oxidizer-to-fuel ratio shift at the low thrust level. Oxidizer-to-fuel ratio shifts occur occasionally at the low thrust levels and indicate a slight maladjustment in the injector core piece. When the propellant valves were reopened to continue the decontamination, control of the servo system had been lost; and the injector pintle had moved to the maximum thrust position. The vehicle accelerated up the vertical track and impacted with the overhanging portion of the tower destroying both the vehicle and the guidance package.

The probable cause of loss of control of the servo system was the failure of the potentiometer which was used to measure the position of the injector pintle. The potentiometer "closed the loop" on the servo system; that is, it told the servo valve when it had moved the pintle to the position which the thrust command signal required. Malfunction of this component would cause the pintle to seek either the full thrust or the zero thrust position. It is believed that the heavy N_2O_4 cloud around the vehicle damaged the feedback potentiometer. The damage resulting from the collision at the top of the tower and the fall back to the ground was so great that it was impossible to ascertain what had caused the malfunction. It was estimated that time from the loss of control of the servo system to impact was 1.5 seconds. The operator of the valve control panel did not have visual contact with the vehicle, and observers were unable to inform him of the malfunction before the vehicle impacted.

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[4] Ibid

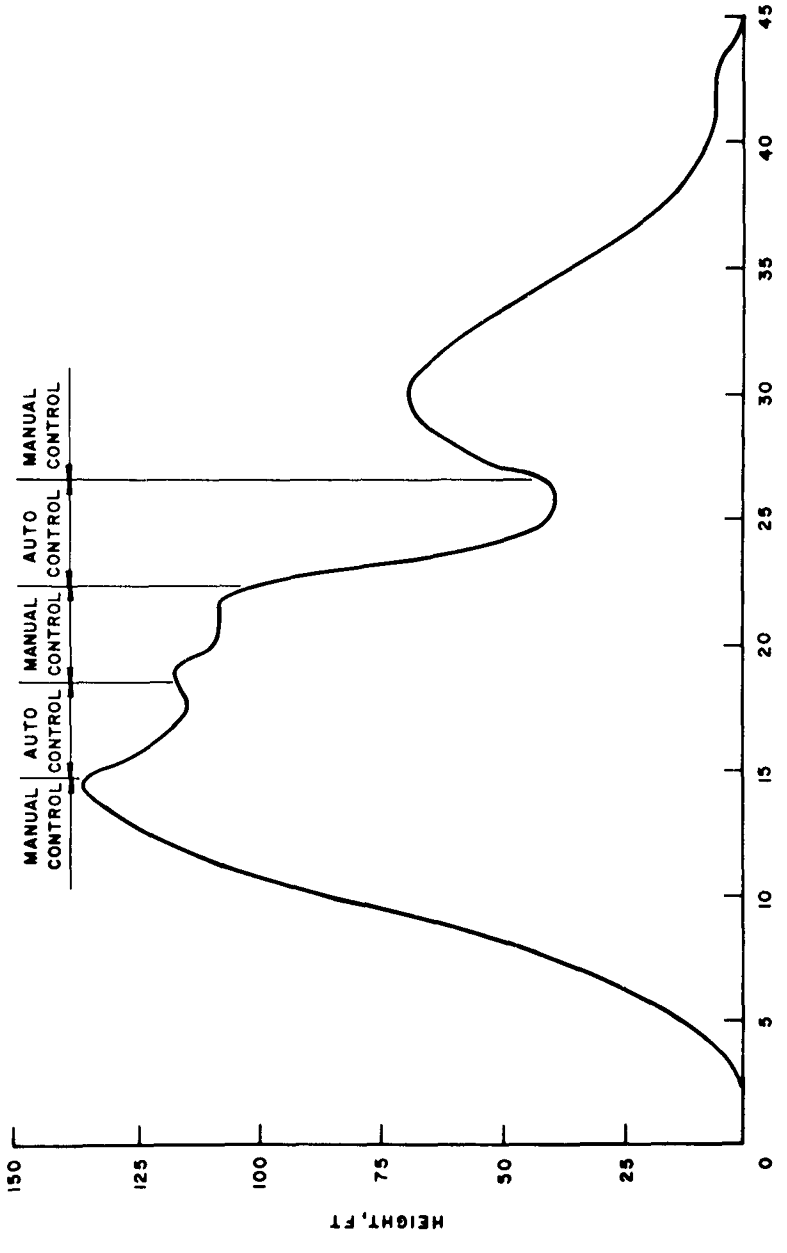

FIG. 11. Vehicle Height Versus Time Profile.

CONCLUSIONS

The initial purpose of the soft-landing vehicle project was completed, and the feasibility of using the NOTS Variable Area Injector to control the thrust of a vertically descending vehicle was demonstrated. It was also demonstrated that control of the retro-thrust of the vehicle's engine was within human capability. However, problems still remain to be solved before the optical scanner could be used to land the vehicle on earth and possibly on the lunar surface.

It is believed that the problems encountered during the flight tests are minor and can be readily solved.

RECOMMENDATIONS

This station has recently made a proposal on a completely free-flight hovering vehicle. This vehicle has total weight of approximately 6,000 pounds, including approximately 2,000-pound payload capability. It would be used for early testing of Apollo vehicle components and for training of astronauts in the control of a soft-landing vehicle.

Many other applications for soft-landing vehicles or hovering instrumentation platforms exist.

All components of a hovering or soft-landing vehicle are "state of the art"; and such a vehicle could be designed, fabricated, and ready for flight testing within a year.

APPENDIX A

TANKAGE AND STRUCTURE DESIGN

The components of tankage and structure of the soft-landing vehicle (1105-R) were obtained from surplus material wherever possible. The weight of the tankage and structure were far above optimum for this reason. Figures 12 and 13 are illustrations of the vehicle with all major components labeled.

A 16-inch diameter spherical tank located at the top of the vehicle was used to store the 3,000 psi nitrogen. This tank had been received in a shipment of surplus material, and its origin and composition are unknown. The tank was hydrostatically tested to insure that it was safe.

The oxidizer tank was made from 6061-T6 aluminum and had been built for a project which had long since been completed. The tank had walls 1/2 inch thick and had been proof-tested to 1,500 psi. This tank was hydrostatically tested to 750 psi after each test to insure that the dilute nitric acid formed in the tank during decontamination had not affected the structural integrity of the tank.

The four fuel tanks were fabricated by welding mild steel schedule 40 pipe caps to each end of a 5-foot long piece of seamless mild steel tubing. Holes were drilled into the pipe caps and standard AN fittings were welded into the holes. One-inch diameter aluminum tubing was used as a manifold to connect each of the fuel tanks.

The fuel tanks provided the backbone of the structure. Structure between the tanks was composed of 1-inch wide by 1/8-inch thick steel strap. A structural component fabricated from this strap was welded to each of the fuel tanks. This structural component was bolted to rings at the top and bottom of the oxidizer tank and at the top of the nitrogen tank, thus, joining the six tanks into an airframe. The combustion chamber and injector assembly were fastened to the ring at the bottom of the oxidizer tank.

A landing gear assembly was welded to the lower end of each fuel tank. The landing gear assembly consisted of telescoping steel tubes which housed a double-acting hydraulic shock absorber and automobile overload coil springs. A cutaway illustration of the landing gear appears in Fig. 14.

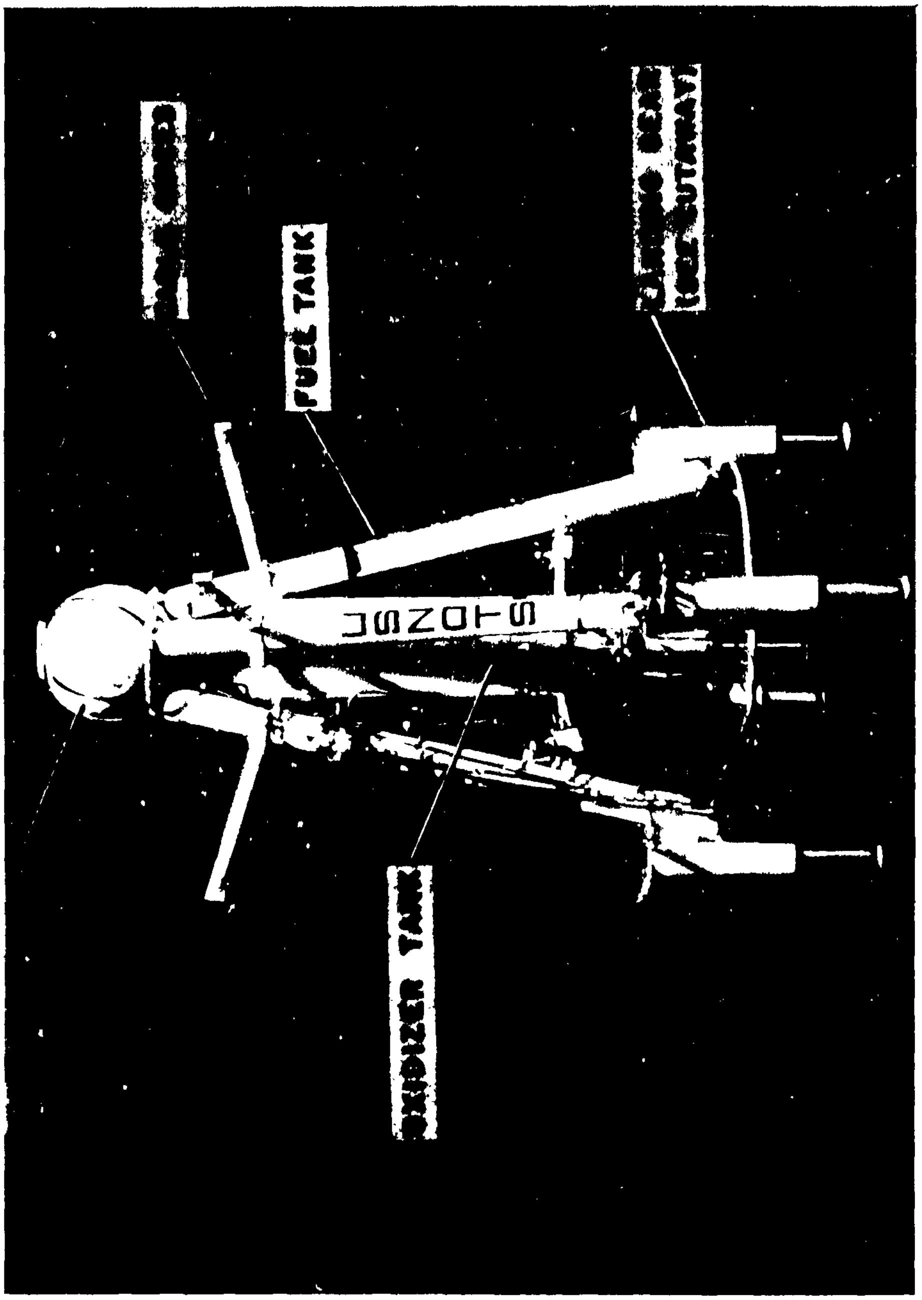

FIG. 12. Vehicle Illustration.

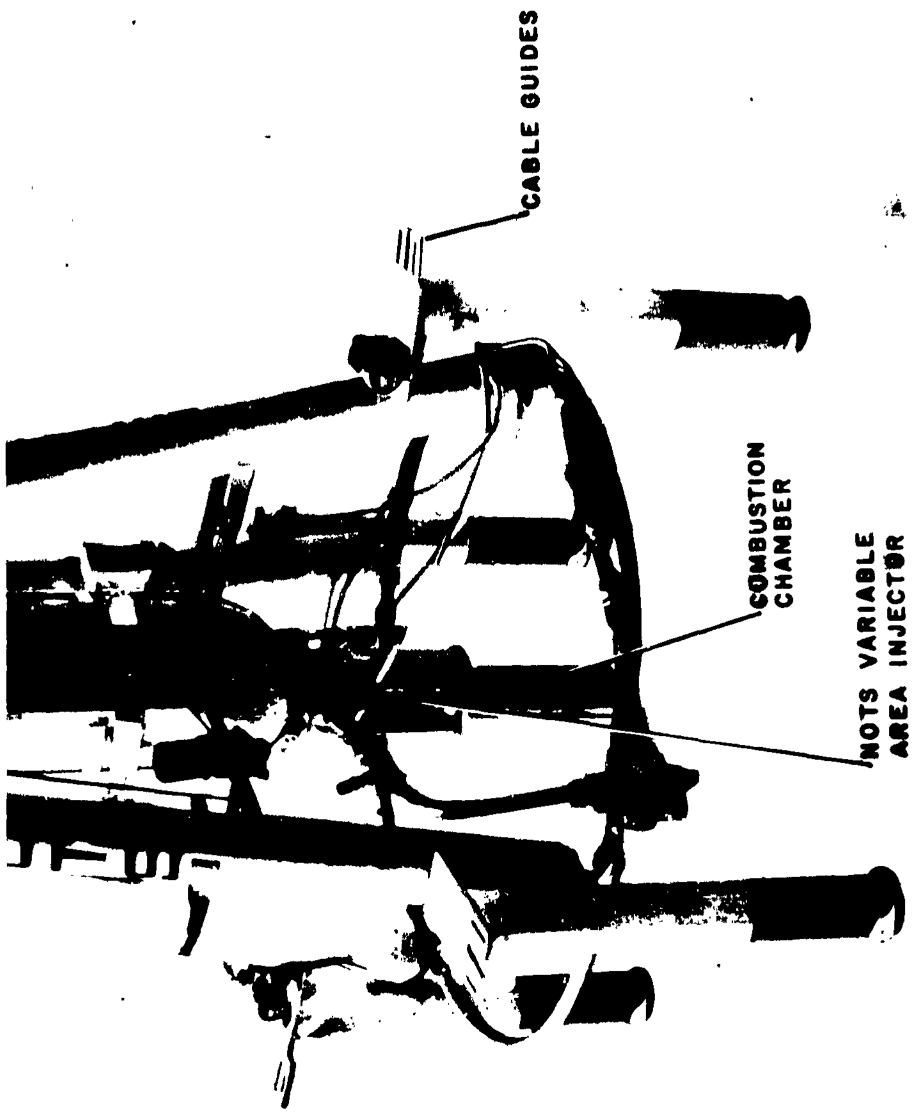

FIG 13. Vehicle Illustration.

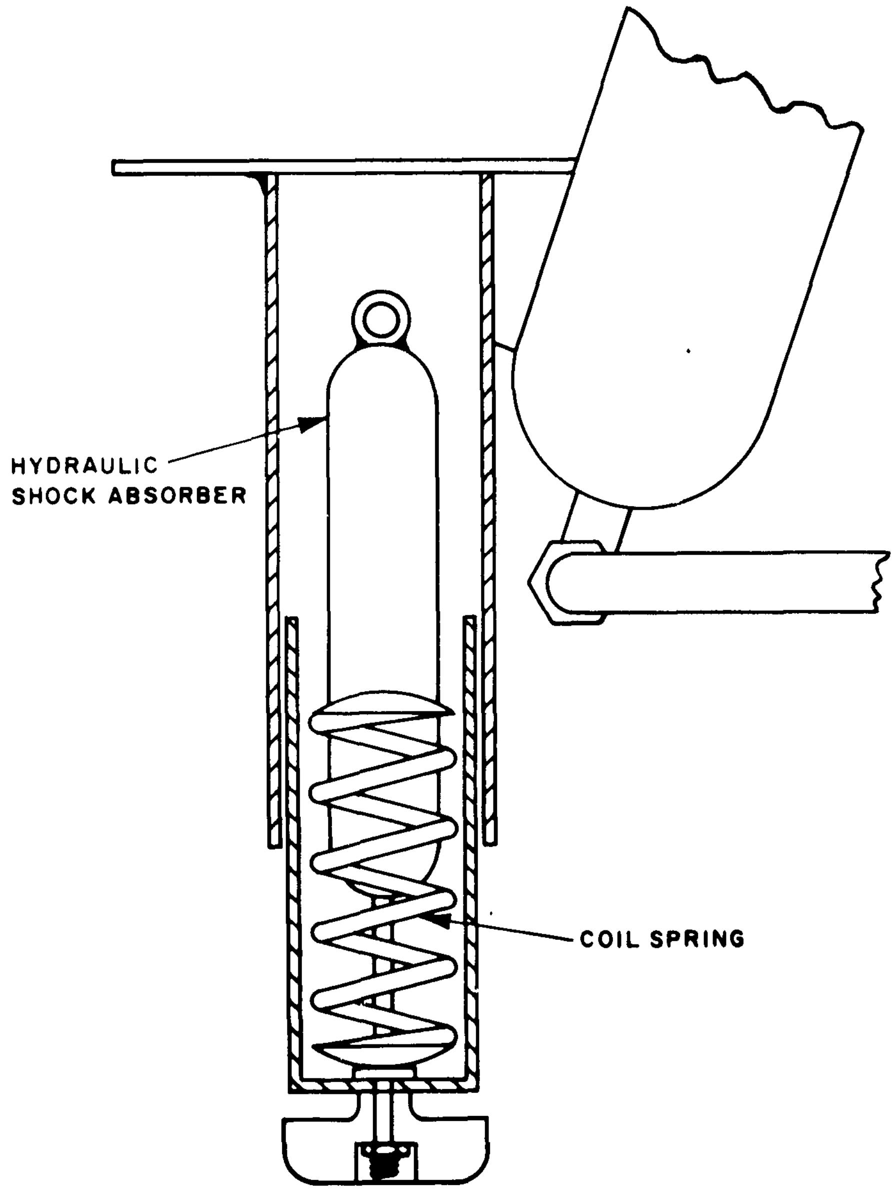

FIG. 14. Cutaway of Landing Gear.

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direction of the vertical axis.

Propellant tank capacity of the soft-landing vehicle was 200 pounds of inhibited red fuming nitric acid and 100 pounds of unsymmetrical-dimethylhydrazine. Total loaded weight of the vehicle was 700 pounds and maximum thrust was 1,300 pounds.

The vehicle successfully completed four captive flight tests. During these tests a maximum height of 155 feet and landing velocities between 3.8 and 8.3 feet per second were achieved. Thrust control was sufficient to allow the observer to hover the vehicle.

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